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A FLUIDIC DEVICE FOR MEASURING CONSTITUENT MASSES OF A FLOWING BINARY GAS MIXTURE

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16. Abstract

A continuous reading mass flow device was developed to measure the component flow of a binary gas mixture. The basic components comprising the device are a fluidic humidity sensor and a specially designed flow calorimeter. These components provide readings of gas mixture ratio, mixture heat capacity, heat dissipated by the calorimeter and the gas temperature rise across the calorimeter. These parameter values, applied in the general definitions of specific heat capacity and the heat capacity of a gas mixture, produce calculated component flow rates of the mixture being metered. A test program was conducted to evaluate both the steady-state and dynamic performance of the device.

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A FLUIDIC DEVICE FOR MEASURING CONSTITUENT MASSES OF A FLOWING BINARY GAS MIXTURE

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SUMMARY

A device was developed to measure the component flow of a binary gas mixture. The basic components comprising the continuous reading device are a fluidic humidity sensor and a specially designed flow calorimeter. The calorimeter provides readings of the gas stream temperature rise produced by a measured amount of heat that is dissipated into the gas stream, and the humidity sensor is used to obtain a continuous calculation of the specific heat capacity of the gas mixture being metered. To produce calculations of the total mass flow and component flow rates of the stream being metered, the heat capacity, heat input, and temperature rise parameters are applied in the general definitions of specific heat capacity and the heat capacity of a gas mixture.

The performance of the device was evaluated by testing it on a closely controlled gas mixture of hydrogen and water vapor. It was found that by properly selecting one of two stream temperature measurement techniques, an accuracy of ±2 percent could be realized over a significant flow range (Reynolds number in the calorimeter exit tube ranged from 1240 to 5540).

The dynamic characteristic of the device was determined by testing its response to a step in the flow rate of a hydrogen test stream. From this data it was found to have a time constant of approximately 4.5 seconds.

INTRODUCTION

In conjunction with a fuel cell dynamics test program undertaken at the NASA Lewis Research Center, a fluidic humidity sensor was developed as an aid in studying the steady-state and non-steady-state mass transport that occurs in hydrogen-oxygen fuel cells. In an open loop mode of operation, the fluidic sensor provides a continuous reading of the humidity of the effluent hydrogen stream of the cell. If the outlet stream hu-

midity, the inlet stream composition, the stoichiometric reactant consumption rate, and the water formation rate are known, a continuous calculation of the rate at which water is rejected from the cell is attainable. This water rejection data can, in turn, provide a measure of the all important operating parameter, the electrolyte volume.

In closed loop operation, the fuel cell water management and temperature control system sets the conditions (temperature and humidity) of the hydrogen stream that is recirculated to the cells, and thus the inlet stream composition is not available for calculating the water rejection rate. A humidity sensor in the outlet stream can be used to measure the mass ratio to obtain a reading of the effective electrolyte concentration. However, the outlet mass flow measurement and, hence, the electrolyte volume are not attainable parameters. To provide these parameters for closed loop testing, a flow-measuring device was contrived which measures the component flow rates of a binary gas mixture. The main elements comprising the instrument are the fluidic humidity sensor and a flow calorimeter.

The basis for operation of the instrument can be found in the definition of specific heat capacity,

$$Q = MC_p(\Delta T)$$

and in the expression for the heat capacity of a mixture of gases,

$$(C_p)_{mix} = \frac{(C_p)_1 M_1 + (C_p)_2 M_2}{M_1 + M_2}$$

The symbols are defined in the appendix.

A schematic block diagram of the instrument is shown in figure 1. The mass ratio output of the humidity sensor provides an instantaneous reading of the gas stream specific heat capacity, and the calorimeter provides values for the amount of heat input Q necessary to produce a measured stream temperature rise ΔT. These values are substituted in the heat capacity equations to provide calculated values for the total and component mass flow rates of a binary mixture.

Our fuel cell dynamics test apparatus was used to produce a variety of stream conditions for testing the device in both steady-state and non-steady-state modes of operation. The test work resulted in a determination of its accuracy and speed of response.

APPARATUS

Fluidic Humidity Sensor

The main element of the humidity sensor, or mass ratio detector, is a delay-line oscillator, a schematic of which is shown in figure 2. The oscillator is designed so that the stream flowing through the nozzle attaches itself to one of the two stream attachment walls and remains fixed there until a pressure pulse produced by the stream traverses the delay line of the side to which it is attached. This pulse forces the stream to the opposite attachment wall, whereupon the process is repeated. It is by this process that an oscillation is established. The frequency of the oscillation is a function of the pulse propagation time through the delay line and any time lag involved in the stream switching from one attachment wall to the other. The frequency is measured by introducing a dynamic transducer into one of the delay lines to pick up the pressure pulsations set up by the oscillating stream. The output of the dynamic transducer is a high impedance charge signal unsuitable as an input to any readout device. Therefore, the transducer output is fed to a charge amplifier to be converted to a low impedance periodic voltage which can then serve as an input to a frequency-to-dc converter to obtain a dc analog readout of the oscillator frequency.

For a given oscillator delay-line length, the switching pulse propagation time is a function of the molecular weight of the stream in question for a given temperature and pressure. Since molecular weight is a linear function of the stream mass ratio, a calibration curve of oscillation frequency as a function of mass ratio can be obtained. A typical humidity sensor calibration curve of output frequency as a function of the mass ratio of water vapor to hydrogen is shown in figure 3. Theory dictates that the stream mass ratio is inversely proportional to the oscillation frequency squared. However, figure 3 indicates that over the range shown, the calibration could be linearized without the introduction of a large error. A more complete description of the instrument plus steady-state and non-steady-state calibration data are presented in reference 1.

In the flow meter application, the fluidic sensor output of mass ratio $\left(M_{H_2O}/M_{H_2}\right)$ provides a continuous reading of the heat capacity of the hydrogen water-vapor exit stream mixture of a fuel cell through the expression

$$(C_p)_{mix} = \frac{M_{H_2}(C_p)_{H_2} + M_{H_2O}(C_p)_{H_2O}}{M_T}$$

or

$$(C_p)_{mix} = \frac{1}{\left(1 + \frac{M_{H_2O}}{M_{H_2}}\right)} \left[(C_p)_{H_2} + \left(\frac{M_{H_2O}}{M_{H_2}}\right) (C_p)_{H_2O} \right]$$

Flow Calorimeter

Of equal importance with being able to obtain an accurate gas stream heat capacity from the humidity sensor is the ability to introduce a metered amount of heat into the flowing gas stream. This required designing and building a flow calorimeter. The calorimeter that was breadboarded is shown schematically in figure 4. It was designed such that the whole heating element and the metering thermocouples are immersed in the gas stream in a thermally isolated volume. The heater element is 36 gage Nichrome wire swaged into a 0.102-centimeter- (0.040-in. -) o.d. Inconel tube. Approximately 30.5 centimeters (12 in.) of heater with a resistance of 8 ohms was coiled on a 0.318-centimeter- (1/8-in. -) diameter mandrel to form the 7.62-centimeter- (3-in. -) long element. The heating is localized by bringing heavy, swaged, stainless steel conductors into the heating tube and making the welded electrical connections internally.

A conduction break is provided on both the entrance and exit sides of the heater tube by making the transition from the heated section to the supply tubes through ceramic-insulated connectors. To eliminate convection losses, the heated tube was vacuum jacketed. The vacuum enclosure is a 13.62-centimeter- (3-in. -) diameter, stainless steel cylinder approximately 15.25 centimeters (6 in.) long. The heater is shielded from radiation losses with an open-ended inner cylinder of highly polished stainless steel. The radiation shield is held within the vacuum jacket by fitting the ends of the shield over wire rings welded to the inside of the vacuum cylinder end plates.

The metering thermocouples consist of a probe in the 0.318-centimeter (1/8-in.) supply line to measure the inlet stream average temperature and a similar couple in the outlet line to measure the outlet stream average temperature at high flow, turbulent stream conditions. In a low flow condition in which the stream in the 0.318-centimeter (1/8-in.) exit tube falls within the laminar regime, the probe reading becomes inaccurate. Therefore, under these conditions the outlet stream measurement is taken from a thermocouple mounted on a screen installed in the heater tube. The screen, which was installed just downstream of the Nichrome element, provides good temperature averaging in a laminar flow condition. The screen itself is a wafer of a nominal 16-mesh-per-centimeter (40-mesh-per-in.), 0.0254-centimeter- (10-mil-) thick, the screen was built up with a layer of epoxy to provide electrical and thermal insulation from the heater enclosure.

Breadboard Design

The schematic for the flow-measuring device, complete with all the electronics necessary to produce a continuous calculation of total and constituent mass flow rates, is shown in figure 5. In the simplest sense, all that is necessary to manually calculate the mass readings are continuous data recordings of the stream mass ratio from the humidity sensor, the dc electrical power input to the calorimeter heater, and the gas stream temperature rise across it. However, the availability of analog computing equipment allowed the complete instrument to be breadboarded and tested.

In this circuit, a diode function generator accepts a frequency analog from the humidity sensor and converts this to a mass ratio analog as per the frequency-to-mass-ratio calibration of the sensor. The mass-ratio analog is then operated on by the various circuit components according to the expression

$$(C_p)_{mix} = \frac{1}{\left(\frac{M_{H_2O}}{M_{H_2}} + 1\right)}\left[(C_p)_{H_2} + \left(\frac{M_{H_2O}}{M_{H_2}}\right)(C_p)_{H_2O}\right]$$

This calculated value of mixture heat capacity is then used along with the calorimeter parameters of gas temperature rise and heat input to calculate the total mass flow according to the expression

$$M_T = \frac{Q}{(C_p)_{mix}(\Delta T)}$$

To calculate the component water flow rate, the mass flow and mixture heat capacity values are then used in the expression

$$(C_p)_{mix} = \frac{M_{H_2}(C_p)_{H_2} + M_{H_2O}(C_p)_{H_2O}}{M_T}$$

or

$$M_{H_2O} = \left[\frac{(C_p)_{mix} - (C_p)_{H_2}}{(C_p)_{H_2O} - (C_p)_{H_2}}\right]M_T$$

To convert the device from use on a stream of hydrogen and water vapor to any other binary gas mixture would require only that the function generator be set up with the appropriate humidity sensor calibration and that the potentiometer settings for the constituent heat capacities be appropriately changed.

Test Apparatus

The fuel cell dynamics test apparatus (ref. 2) was used to generate the mixture of hydrogen and water vapor on which the flow-measuring device was tested. The rig provided a good standard, since the closed loop controllers of which it is comprised are capable of controlling with a high degree of accuracy the stream parameters of temperature, pressure, flow rate, and mixture ratio. Aside from being able to provide an accurately controlled steady flow, the test rig has the dynamic testing capability to produce fast response perturbations in any one of the stream parameters while automatically holding the other parameters constant. A more complete description of the test apparatus is given in reference 2.

PROCEDURE

The fuel cell dynamics test apparatus was used to generate the closely controlled hydrogen and steam mixture on which the flow device was tested. Tests were run over flow ranges that produced both laminar and turbulent flow conditions in the heater exit tube of the calorimeter. Also, various heater power levels were tried to determine whether the heat input had to be optimized with the gas flow range to maintain the accuracy of the instrument.

To test the instrument's dynamic characteristics, response tests were conducted by measuring the speed at which it responds to changes in test stream flow rate.

RESULTS AND DISCUSSION

The data presented in table I exemplify the performance that was obtained from the instrument. The various test mixtures were generated by holding the steam component at a constant flow rate of 0.109 kilogram per hour, (0.24 lb/hr) while varying the hydrogen flow over a range of values. Two sets of data were taken. In one set, the screen-mounted thermocouple was used to obtain the temperature of the gas stream at the outlet of the calorimeter heater. In the other set, the thermocouple probe mounted in the 0.318-centimeter (1/8-in.) heater-exit tube was used.

These data are illustrated graphically in figure 6, where the hydrogen component flow of the test stream is plotted against the percent error of the hydrogen flow calculated by the instrument. The plot illustrates how the accuracy of the instrument is affected by the technique used to measure the stream temperature rise in the calorimeter. At a low flow condition in which the stream flow in the 0.318-centimeter (1/8-in.) heater-exit tube of the calorimeter is in the laminar regime, the screen-mounted thermocouple provides the more accurate data. The inaccuracy of the data obtained with the use of the exit stream probe may be attributed to the fact that in a laminar flow condition a radial temperature gradient exists in the exit tube stream. Thus, the probe, being mounted in the center of the tube, records a higher-than-average stream temperature, and the resulting flow data comes out low.

In midrange, both measurement methods provide accurate data. However, as the stream in the exit tube approaches the turbulent regime, the data taken from the screen-mounted thermocouple become less accurate. In this range, the flow in the 0.636-centimeter (1/4-in.) heater tube is still within the laminar regime. However, the radial temperature gradient in the gas stream is apparently too large to be averaged out by the screen. Since the metering thermocouple is mounted at the center of the screen, temperatures higher than the stream average are used in the flow calculation. This again results in erroneous readings which are lower than the true values. On the other hand, the turbulent condition in the heater exit tube eliminates any radial temperature gradient and thus allows the exit stream probe to record an average stream temperature. The data in this portion of the flow range are slightly but consistently higher than the true flow data. This error is probably due to the small heat loss that occurs between the heater tube exit and the line probe location.

Thus, by considering the range of the device as being defined by a composite of the data calculated with the use of the screen thermocouple and the exit line probe, a very acceptable accuracy of ±2.0 percent is realized over a large flow range. However, an obvious shortcoming in having to select the proper readout thermocouple is that this presupposes at least a rough idea of what stream conditions exist in the heater exit tube of the calorimeter and thus some of the characteristic generality of the device is lost.

Data were taken at various calorimeter-heater power levels in a range from 4 to 20 watts. Below 4 watts, the error over the whole flow range becomes significant, probably because at low power levels the temperature rise across the heater is small and cannot be read with sufficient accuracy. Above 20 watts, the device again becomes inaccurate, particularly in the high flow range. This is probably due to the proportionately higher heat loss that occurs between the calorimeter-heater tube and the exit line probe at the elevated temperature and flow conditions.

The instrument's dynamic response was checked by introducing step changes in the flow rate of a pure hydrogen test stream. A typical response transient, in which the hydrogen flow was stepped from 0.089 kilogram per hour, (0.195 lb/hr) to 0.111 kilo-

gram per hour (0.245 lb/hr) is shown in figure 7. By assuming this transient to be the step response of a first order system, a time constant of approximately 4.5 seconds can be read off the curve. By observing the flow step response of the temperature rise across the calorimeter, the transient shown in figure 7 was found to be largely the result of the thermal response characteristic of the heater. This was not unexpected, since the gas volume of the humidity sensor (fluidic oscillator) is very small, and the oscillator and calorimeter are close-coupled to minimize the total line volume of the instrument. Thus, any response lag due to the gas volume of the device was effectively eliminated.

A constraint placed on the instrument by the fluidic oscillator is that the incoming test stream must be at the temperature and pressure at which the oscillator was calibrated, since the oscillator frequency is both temperature and pressure sensitive. A biasing system to compensate for changes in one or both of these parameters could be constructed, but, not without the introduction of a considerable degree of complexity.

SUMMARY OF RESULTS

The fluidic flow-measuring device was tested over a flow range in which the water vapor component of a mixture of hydrogen and water vapor was held constant at 0.109 kilogram per hour (0.24 lb/hr) and the hydrogen component was varied from 0.0273 kilogram per hour (0.060 lb/hr) to 0.400 kilogram per hour (0.88 lb/hr). Over this range, the instrument was accurate to within ±2 percent of the test flow. However, to get this accuracy over the whole range, it was necessary to select the calorimeter outlet stream thermocouple on the basis of the flow regime in the calorimeter exit tube. In a laminar flow condition, a thermocouple mounted on a screen installed at the end of the calorimeter heater tube was used to get an average heater outlet temperature reading; while in a turbulent condition, a probe mounted in the center of the exit tube was used. Though ±2 percent is the accuracy of the whole breadboarded instrument, it was found that the calorimeter accounted for the major portion of the error.

The instrument's response to a step in flow rate was checked and found to be that of a characteristic first order system with a time constant of 4.5 seconds. This was found to be largely the result of the response of the calorimeter.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 20, 1972,
502-25.

APPENDIX - SYMBOLS

$(C_p)_{H_2}$	specific heat capacity of hydrogen, J/(kg)(K); Btu/(lbm)(^{o}F)
$(C_p)_{H_2O}$	specific heat capacity of water vapor, J/(kg)(K); Btu/(lbm)(^{o}F)
$(C_p)_{mix}$	specific heat capacity of a mixture of gases, J/(kg)(K); Btu/(lbm)(^{o}F)
$(C_p)_1$	specific heat capacity of component 1 of a mixture of gases, J/(kg)(K); Btu/(lbm)(^{o}F)
$(C_p)_2$	specific heat capacity of component 2 of a mixture of gases, J/(kg)(K); Btu/(lbm)(^{o}F)
M_{H_2}	mass flow rate of the hydrogen component of a mixture of hydrogen and water vapor, kg/hr; lbm/hr
M_{H_2O}	mass flow rate of the water vapor component of a mixture of hydrogen and water vapor, kg/hr; lbm/hr
M_T	total stream mass flow rate, kg/hr; lbm/hr
M_1	mass flow rate of component 1 of a mixture of gases, kg/hr; lbm/hr
M_2	mass flow rate of component 2 of a mixture of gases, kg/hr; lbm/hr
Q	heat input to the gas stream per unit time, J/hr; Btu/hr
ΔT	gas-stream temperature rise, K; ^{o}F

REFERENCES

1. Prokopius, Paul R.: Use of a Fluidic Oscillator as a Humidity Sensor for a Hydrogen-Steam Mixture. NASA TM X-1269, 1966.

2. Prokopius, Paul R.; and Hagedorn, Norman H.: Investigation of the Dynamics of Water Rejection from a Hydrogen-Oxygen Fuel Cell to a Hydrogen Stream. NASA TN D-4201, 1967.

TABLE I. - FLOWMETER TEST DATA

[Heater power, 12.3 W (maintained constant); heater inlet temperature, 367 K (200° F); ambient pressure in heater, 1.01×10^5 N/m^2 abs (14.7 psia); steam component flow rate, 0.109 kg/hr (0.24 lb/hr).]

Measured flow rates of hydrogen component test stream		Calculated hydrogen component flow rates based on temperatures obtained with screen heater outlet		Calculated hydrogen component flow rates based on temperatures obtained with thermocouple probe in heater exit tube	
kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr
0.0273	0.0600	0.0268	0.0589	0.0245	0.0539
.0363	.0800	.0361	.0795	.0331	.0728
.0455	.100	.0455	.101	.0418	.0920
.0546	.120	.0541	.119	.0509	.112
.0637	.140	.0636	.140	.0591	.130
.0727	.160	.0740	.163	.0682	.150
.0818	.180	.0810	.178	.0767	.169
.0908	.200	.0900	.198	.0864	.190
.1000	.220	.0995	.219	.0958	.211
.1090	.240	.1080	.237	.1060	.234
.1180	.260	.1180	.260	.1160	.255
.1270	.280	.1280	.281	.1250	.275
.1450	.320	.1460	.322	.1440	.317
.1640	.360	.1640	.360	.1630	.359
.1820	.400	.1820	.399	.1820	.401
.2000	.440	.1980	.437	.2010	.442
.2180	.480	.2160	.475	.2180	.480
.2360	.520	.2340	.515	.2380	.523
.2540	.560	.2510	.551	.2550	.561
.2730	.600	.2690	.591	.2750	.604
.2910	.640	.2850	.627	.2940	.646
.3090	.680	.3020	.665	.3110	.684
.3270	.720	.3190	.701	.3290	.723
.3450	.760	.3370	.742	.3490	.767
.3640	.800	.3530	.775	.3660	.804
.3820	.840	.3690	.811	.3860	.848
.4000	.880	.3840	.845	.4050	.891

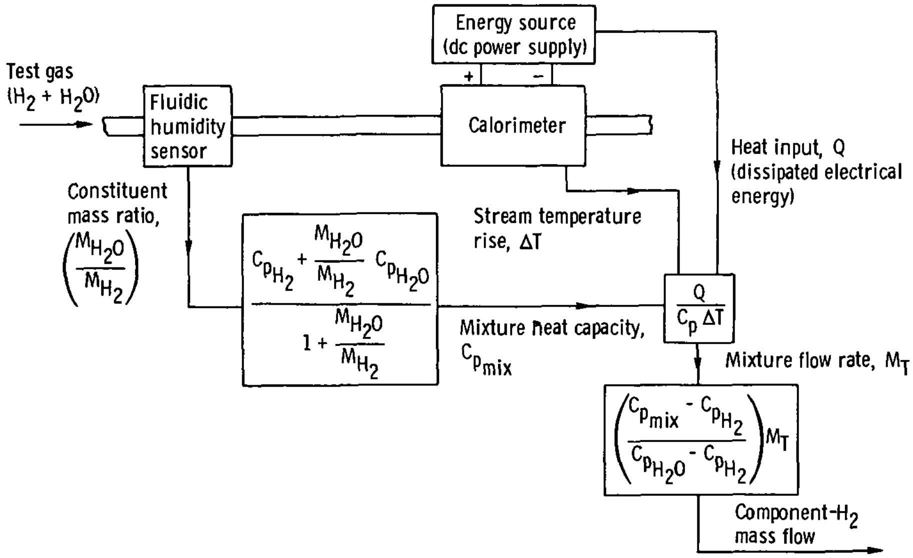

Figure 1. - Schematic diagram of flow measuring instrument.

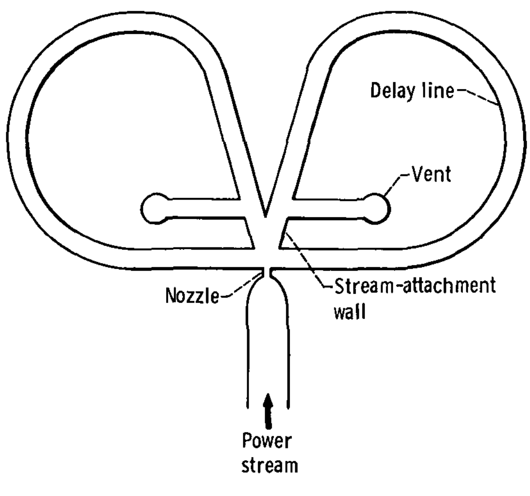

Figure 2. - Schematic diagram of fluidic oscillator.

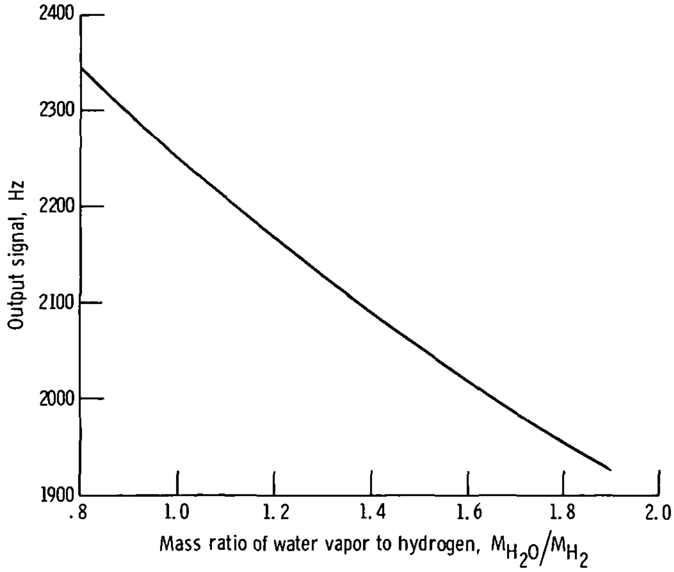

Figure 3. - Steady-state calibration of humidity sensor.

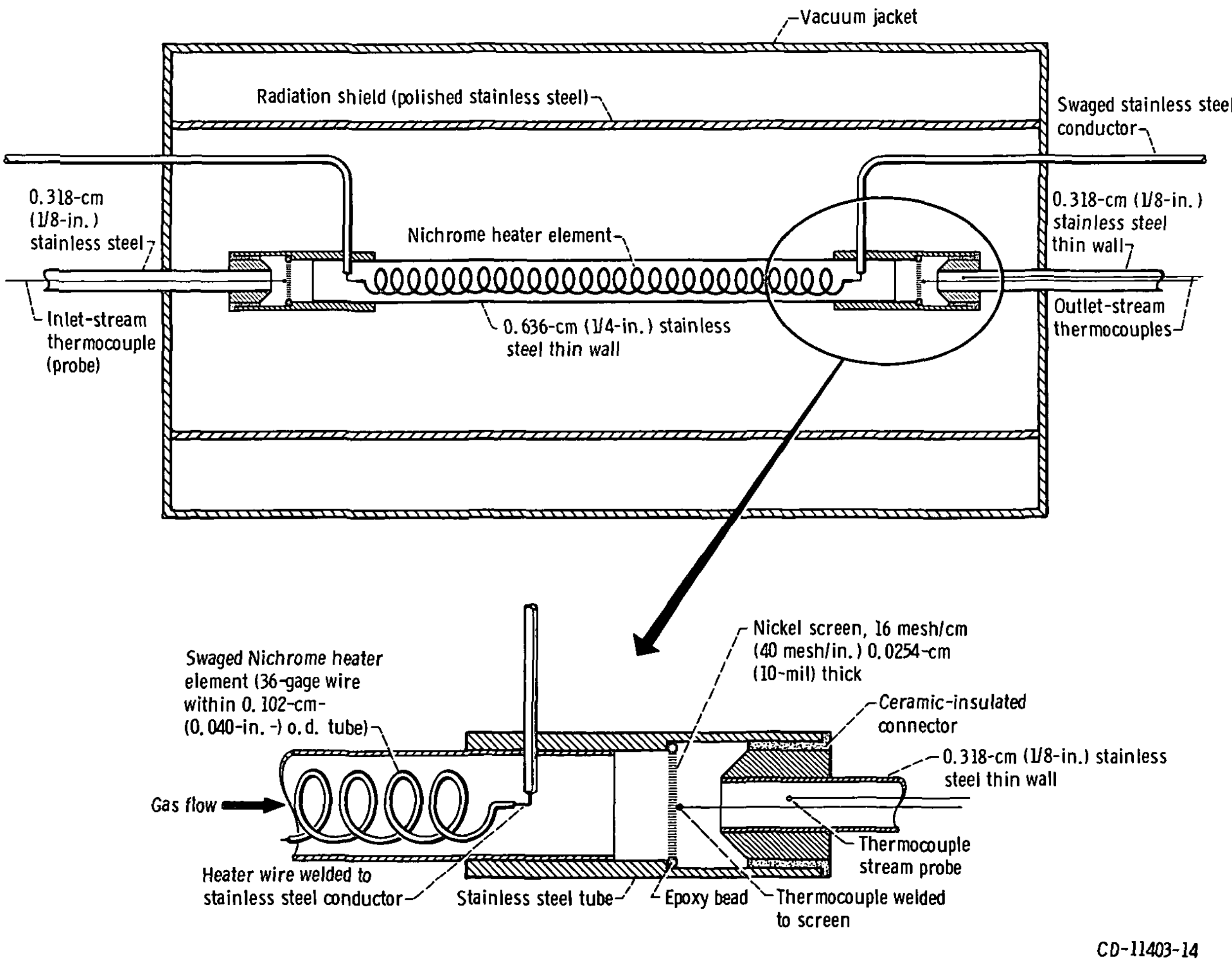

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Figure 4. - Flow calorimeter.

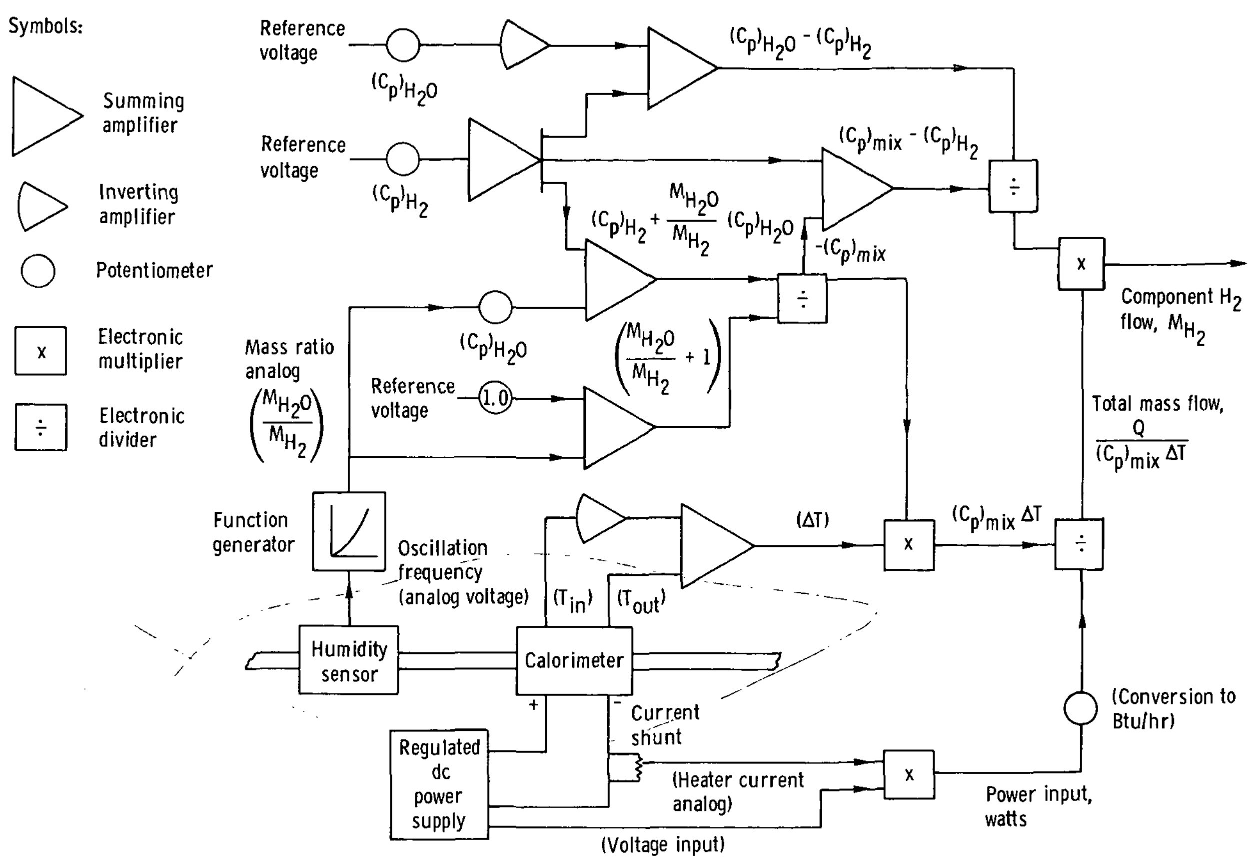

Figure 5. - Instrument breadboard schematic.

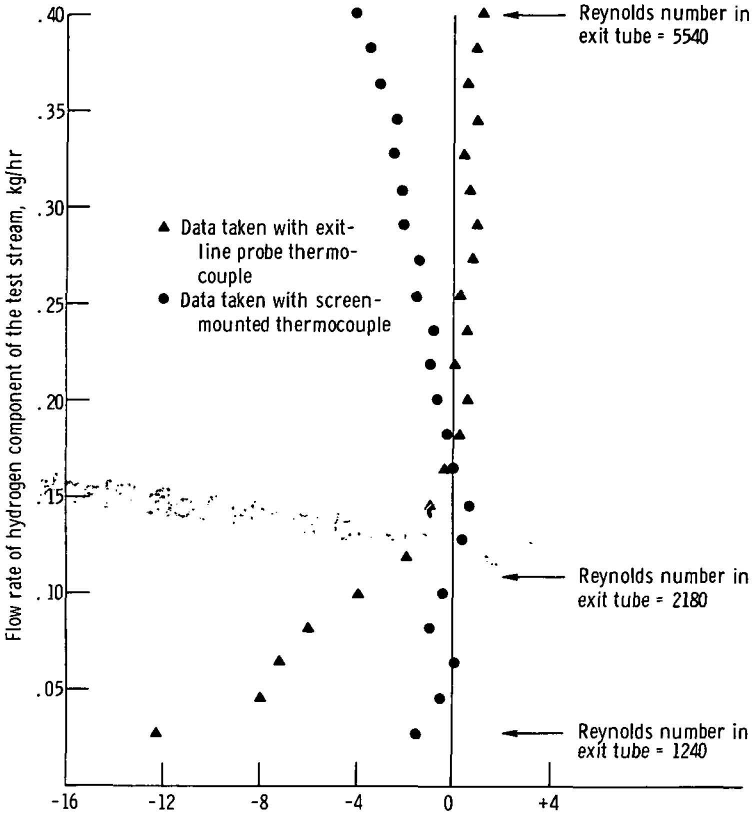

Figure 6. - Instrument error data.

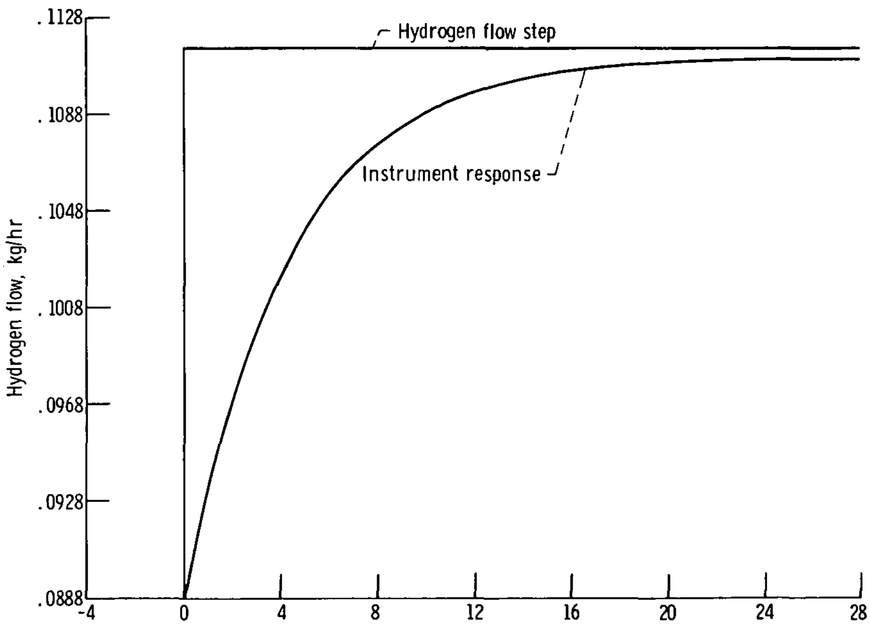

Figure 7. - Instrument step response.

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